Final Report - Reliable Wireless Data Acquisition and Control Techniques within Nuclear Hot Cell Facilities

DOE Project DE-FG07-98ID13636

Principal Investigator: James L. Kurtz, University of Florida
Co-Principal Investigator: James Tulenko, University of Florida

Report Period: July 1, 1998 – September 30, 2000

1.0 Project Summary

On this NEER project the University of Florida has investigated and applied advanced communications techniques to address data acquisition and control problems within the Fuel Conditioning Facility (FCF) of Argonne National Laboratory-West (ANL-W) in Idaho Falls. The goals of this project have been to investigate and apply wireless communications techniques to solve the problem of communicating with and controlling equipment and systems within a nuclear hot cell facility with its attendant high radiation levels. Different wireless techniques, including radio frequency, infrared and power line communications were reviewed. For each technique, the challenges of radiation-hardened implementation were addressed. In addition, it has been a project goal to achieve the highest level of system reliability to ensure safe nuclear operations. Achievement of these goals would allow the eventual elimination of through-the-wall, hardwired cabling that is currently employed in the hot cell, along with all of the attendant problems that limit measurement mobility and flexibility.

1.1 Phase 1 Summary of Objectives and Accomplishments

Phase 1 of the project, performed in the first project year, addressed three objectives and their corresponding task areas: the demonstration of wireless data acquisition systems that may be feasible for hot cell applications, investigation of innovative wireless techniques for nuclear applications, and radiation-hardening considerations. Several questions were addressed in Phase 1 in order to achieve the project goals. These questions were related to the performance of wireless equipment in hot cell environments, the degree of radiation tolerance of certain wireless components, and techniques to mitigate radiation effects on components. Accordingly, these questions were addressed in the three Phase 1 tasks. The objectives and accomplishments of these tasks, with clarified statements of Phase 1 objectives, are described below.

Objective 1: Determine communications techniques that offer the best potential for penetrating the shielded walls used in nuclear hot cells and for alleviating the multipath signal effects encountered in this environment.

Accomplishments: Radio frequency (RF) and infrared (IR) wireless communications transceiver techniques were evaluated in Phase 1 and both frequency regimes showed viability for outside-to-inside hot cell and within hot cell communications. Power line techniques were similar to RF wireless techniques in their capabilities, but had other limitations, such as low data rates. Power line techniques were eliminated from further consideration. Several specific accomplishments were achieved during Phase 1 through a collaborative effort with researchers at ANL-W. These accomplishments helped to identify the most fruitful approaches. Functional hardware demonstrations using primarily 2.4 GHz RF wireless transceivers and associated data acquisition components were performed at the University of Florida and subsequently at ANL-W. The RF wireless demonstrations utilized commercial-off-the-shelf (COTS) components that have the potential to be constructed in radiation-tolerant designs. Methods for the realization of radiation-tolerant data acquisition component designs have been investigated as part of Task 2 and Task 3 discussed below. Another important accomplishment in this task was the demonstration of RF signal penetration and data communications through the hot cell walls at ANL-W using wireless communications components at both 900 MHz and 2.4 GHz [1,2]. Future testing would be required to measure the attenuation of the RF signal through the hot cell walls and the effects of multipath on the communications signal. The demonstration of RF signal penetration and data communications through the hot cell walls is a significant accomplishment that allowed more emphasis to be placed on radiation-hardened component techniques, specifically for RF wireless communications. Infrared data communications techniques were also investigated as an alternative wireless transceiver technique and several specially constructed infrared communications transceivers were tested. Several limitations were identified with infrared communications techniques. For IR, line-of-sight communications is usually required which may necessitate repeaters, the modulation techniques and electronics required are similar to those required for RF communications, and the optical components degrade in radiation environments. While IR transceiver techniques may be useful in combination with RF techniques for hot cell wireless data acquisition problems, to improve reliability and/or mitigate multipath signal effects, it was decided to concentrate on specific data acquisition components and RF techniques in order to develop a complete conceptual system.

Objective 2: Investigate robust data acquisition and control techniques that are able to operate in harsh radioactive environments without cabling.

Accomplishments: The wireless communications transceiver components and the data acquisition and interface components used in nuclear hot cell environments must be physically and environmentally robust in addition to radiation-tolerant. While many COTS components are adequate to handle the communications protocols, data rates, and measurement functions required, they are designed with high levels of circuit integration and microprocessors. Many of the integrated circuits and microprocessors currently employed in these designs are not radiation-tolerant nor are they available in radiation-hardened equivalents. Several alternative approaches have been considered to deal with this aspect of the hot cell wireless communications problem. Task 2 has concentrated on design techniques which optimize the use of currently available radiation-hardened components, while Task 3 has concentrated on evaluating radiation effects and hardening a broader class of electronic components.

One approach to improve the radiation tolerance of the wireless data acquisition system is to simplify the circuit or component design and provide only the level of functionality needed. For example, a data acquisition component may be designed to have limited capabilities such as read (data) only or write only, rather than full two-way data communications. This limited functionality will often suffice for the data acquisition and control needs within nuclear hot cells. Limited functionality translates into a simpler component design that may allow the elimination of high-level integrated circuits (ICs) and microprocessors. After high-level ICs have been eliminated or substantially reduced, a design can be realized with discrete components or other integrated circuits that can be obtained in radiation-hardened versions. The University of Florida has collaborated with ANL-W researchers to determine the type of functionality needed for current and projected hot cell measurements. Fortunately, many near-term needs involve simple analog signal measurements, such as thermocouple measurements, that can be achieved with a simplified analog-to-digital converter and interface circuit design. During Phase 1 an analog-to-digital (ADC) converter was built and tested using components that can be obtained in radiation-hardened versions. This ADC converter interfaces to a standard RS-232 digital communications interface and will perform many of the analog voltage measurement requirements in the FCF.

A second approach that has been used to improve the overall radiation tolerance of the wireless data acquisition system has been to modularize functions. High and low radiation-tolerant circuit functions have been grouped in a way to maximize operational time of several modules and to minimize module replacements within the hot cell. An example is an RS-232 interface module designed for hot cell wireless data acquisition systems; this interface module is universally compatible with many wireless transceivers. During Phase 1 an RS-232 network module was designed and tested that will handle all communications between the designed data acquisition (DAQ) modules and wireless transceivers. Since the required components in the network module are discrete digital components, the design should be capable of operation to at least 1 MRad total dose when constructed with available radiation-hardened components.

Objective 3.: Investigate radiation-hardening techniques to mitigate the effects of radiation on data communications components.

Accomplishments: Understanding the affects of radiation on electronic components is an extremely important aspect of designing radiation-hardened or radiation-tolerant systems. Certain electronic components and devices utilize technology that is more inherently immune to radiation effects, i.e., Gallium Arsenide, SOI, and SOS devices. Many system components utilize complementary metal-oxide semiconductor (CMOS) devices that are more susceptible to radiation. By characterizing failure mechanisms and failure rates, those devices that are more radiation sensitive can be either improved or possibly removed from a design. This task concentrated on examining critical data acquisition and RF wireless circuit components to better understand where failures are occurring. Also, literature searches were performed to identify those semi-conductor processes that are more inherently radiation-tolerant.

Early testing at ANL-W showed that a 900 MHz wireless RF transceiver failed within less than 24 hours of operation when inserted into the FCF [1]. One of the failed components in the 900 MHz transceiver was identified as a micro-controller. Subsequently, a Motorola MC68HC11 micro-controller similar to the failed device in this transceiver was tested in the UF Cobalt Irradiation Facility. This IC is built with high-density CMOS technology. While monitoring functions on the micro-controller, a hard failure occurred at 12 kRad total dose. Micro-controllers have been identified as one radiation-sensitive component. The University of Florida consulted with Motorola and discussed techniques for radiation-hardened micro-controllers, microprocessors, and other devices from the Motorola Space Electronics group.

In an effort to identify other radiation-induced failures the University of Florida obtained two additional COTS, 2.4 GHz RF wireless transceivers for radiation testing and evaluation. Through a cooperative effort with the transceiver manufacturer, a test program and special test software were developed to exercise and evaluate the transceiver during irradiation. The transceivers were irradiated while actively communicating, with the result being that the devices failed at approximately 13 kRad total dose. While the exact component failure was not identified, the transceivers contained controllers similar to the controllers that failed in earlier tests at nearly the same total dose. These failures were motivation to eliminate such controllers from future designs.

A key aspect of initial radio frequency wireless design concepts was the requirement for sufficient RF transmission through the window(s) and walls of the hot cell to allow communication with internal slave transceivers. Tests at ANL-W were preformed at 900 MHz and 2.4 GHz with commercial components, which show that spread spectrum communication can be achieved through the hot cell walls [1,2] without adversely affecting certain radiation monitors.

Detailed accomplishments in Year 1 of the NEER project were submitted in a technical report to Argonne National Laboratory-West for comments and collaboration [3]. Phase 2 efforts in Year 2 concentrated on completing an RF wireless design.

1.2 Phase 2 Summary of Objectives and Accomplishments

Phase 2 of the project, performed in the second project year, addressed two task areas: the implementation of wireless data acquisition systems based on using wireless RF techniques and, additional demonstrations and tests of the wireless techniques and components.

Objective 4: Implement reliable wireless communications techniques for use within nuclear hot cell facilities at ANL-W.

Accomplishments: One of the most important accomplishments of this task was the completion of a complete radiation-hardened data acquisition system design based on the previously investigated (in Phase 1) National Instruments Fieldpoint system. The system layout shown in Figure 1 allows the measurement and control of a number of processes within a hot cell from outside the hot cell, via wireless connections, with signals passing through the hot cell windows. The system has one Master transceiver for each Network Module that can control up to 16 Slave nodes. Multiple Master units are not allowed unless there can be some guarantee that they will not initiate communications simultaneously. The Slave nodes contain a Radio Transceiver, Network Module and up to four DAQ Modules of possibly different types. The network layout is a point-to-multi-point configuration. A Network Module that controls the DAQ modules and interfaces digital data (RS-232) to/from an RF transceiver was designed, built, and functionally tested. All parts for the Network Module are available in radiation-hardened versions.

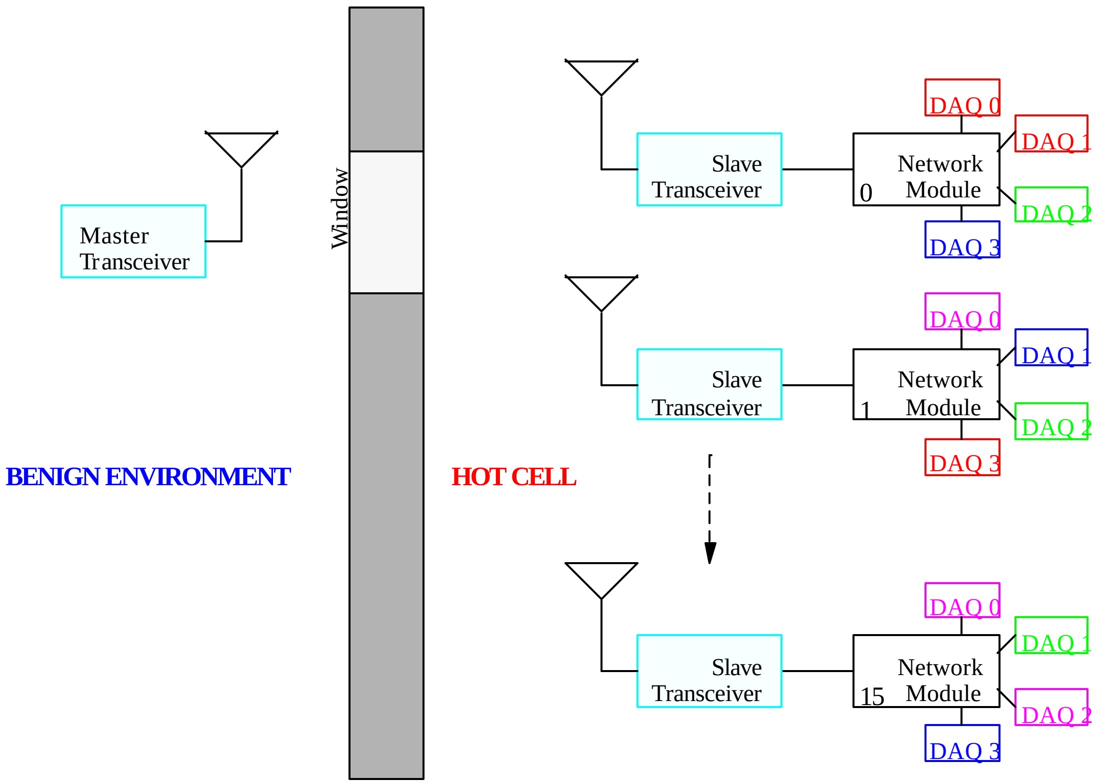

Figure 1. Wireless data acquisition system layout

Initial DAQ module design work for this task focused on the data acquisition and control function components that could be used with a wireless RF system. Hardware for these functions is less complex and the components are more available than for RF transceivers. It was decided to make the data acquisition (DAQ) modules interface to a wireless transceiver via a standard RS-232 interface. Any subsequent wireless communication device could be adapted to or designed to work with this RS-232 interface. The RS-232 interface also allowed for simple control of the DAQ hardware by a computer during the testing phases of the design.

A single channel analog-to-digital converter (ADC) to RS-232 circuit was the first DAQ design that was built. The ADC circuit was initially implemented in Phase 1 using non-radiation hardened components that could be replaced with radiation-tolerant components pin-for-pin. Radiation-tolerant components were obtained and an ADC design with 300 kRad total dose capability resulted. This initial ADC to RS-232 circuit design helped identify the specifications and verify the approach for the remainder of the system.

The design of several other data acquisition modules was also completed as part of this task. In addition to the initial ADC, an 8-channel digital output module and a digital input/output module were designed, built and functionally tested. The digital input/output module was constructed using radiation-hardened parts and radiation tested to greater than 45 MRad total dose (although the circuits are guaranteed by the manufacturer to 1 MRad total dose). This is indicative of the actual radiation limit of the other DAQ modules, as they are designed with similar radiation-hardened CMOS integrated circuits. Paper designs have been completed for the several DAQ modules. These modules are (with expected minimum radiation total dose limits in parentheses): 16-channel ADC module (300 kRad total dose), 64-channel digital input module (1 MRad total dose), 8-channel digital input module (1 MRad total dose), 8-channel switch selectable digital I/O module (1 MRad total dose), and a single-channel analog output module (100 kRad total dose). Those components with a minimum of 1 MRad total dose are expected to be much higher, based on the testing of the digital input/output module.

The RF transceiver is the most complex design for the wireless data acquisition system. The basic approach for a radiation-tolerant wireless transceiver design is to use a simple modulation/demodulation scheme that can be implemented in primarily passive components that are inherently radiation-tolerant. The modulation/demodulation circuits comprise the lowest frequency and first intermediate frequency of the transceiver design. The RF stage takes the modulated intermediate frequency signal and translates the signal to a frequency suitable for radio transmission. For this design, the radio frequency is 2.4GHz. Gallium Arsenide components are used in the RF stage for amplifiers, filters, mixers, etc., as these devices are inherently radiation-tolerant. Gallium Arsenide amplifier test circuits were built and radiation tested to greater than 6 MRad total dose with essentially no change in performance.

A complete RF transceiver, except for local oscillators, has been designed, constructed, and partially tested. Laboratory oscillators are being used to functionally test the design. As noted above, to enhance radiation tolerance, most of the lower- or intermediate-frequency circuitry is passive circuitry, while the higher frequency circuitry uses Gallium Arsenide integrated circuits. The current design will convert digital data at rates up to 128 kBit/s to RF and vice versa, with virtually no errors. Data rates to near 1 Mbits/s were demonstrated by operating at the intermediate frequency and bypassing the RF stages. Further work is required on this design to complete the local oscillators to accommodate frequency drifts between transmitters and receivers. Also, schemes for carrier sensing and for multiple RF channels will need to be investigated to utilize and expand the data acquisition system concept. This work must be completed in order to implement a complete radiation-hardened wireless data acquisition system.

A paper describing the salient accomplishments of the NEER project through the beginning of the second year, was written and presented at ICONE 8, the 8th International Conference on Nuclear Engineering in Baltimore, MD April 2-6, 2000. The paper appears in the proceedings for that conference [4].

Objective 5.: Demonstration of a wireless data acquisition system with hot cell applications.

Accomplishments: A major part of this task has focused on additional testing of the RF transceiver and selected tests with DAQ modules to complete a system level wireless data acquisition system suitable for practical applications. While the basic design of the RF transceiver was completed on task 4, further testing was required to characterize the effects of frequency offsets between transmitters/receivers and to design schemes for frequency locking to compensate for these drifts. Both filter and phase-locked loop techniques have been examined. Filter techniques have been implemented, because passive-filter techniques are more radiation-tolerant, and will partially accommodate these frequency drifts. Additional tests are required to determine if phase-locked loop techniques may be required before completing the transceiver design. Other tests will also eventually be required inside a hot cell environment to characterize the effects of RF path loss (attenuation) and multipath.

Tests have been performed with the DAQ modules to simulate typical measurement conditions. Analog voltages of varying amplitudes and frequencies have been tested with the ADC modules. These tests indicate that thermocouples and other low-frequency analog processes can be easily measured with the current ADC design. Digital data from computers has been successfully transferred to the digital input modules and vice versa. Therefore, digital data can also be measured or controlled with the available module designs.

As part of this task, further discussions and a meeting were held with engineers at ANL-W to discuss possible future applications of the wireless components. In addition to measurement and control within the fuel conditioning facility, there is interest in the use of the finished radiation-hardened wireless system for measurement and control in the planned Remote Treatment Facility (RTF) at ANL-W. The RTF will increase both the volume and types of nuclear material that may be handled at ANL-W. By using wireless components of the type designed for the NEER project, internal cabling and maintenance could be significantly reduced in the RTF. These applications are encouraging reasons to continue the development of wireless components that have been developed thus far on this NEER project.

Details of accomplishments achieved during the NEER project were submitted to Argonne National Laboratory-West near the end of the second year of the project [5]. A second report with test procedures and results for all related irradiation testing was also submitted in the second year of the project [6]. Several presentations were made during the NEER project at ANL-W and at the ICONE-8 conference, as listed below.

References:

1. Henderson, S., R. Stewart, and M. Inskeep, "Investigation of wireless signal transmission for control and measurement of hot cell equipment," LDRD summary report 1999.
2. Henderson, S., R. Stewart, M. Inskeep, and G. Mitchell, "Test Report FCF Radiation Monitor RF Compatibility at 2.4 Gigahertz, ANL-W Test Report March 1, 1999.
3. Cowdery, J. J., J. Kurtz, J. Tulenko, D. Schoenfeld "Modular Wireless Data Acquisition System for use in High Radiation Environments," technical report on NEER Project DE-FG-07-98ID13636, submitted to Argonne National Labs-West, 1999.
4. Kurtz, J. L., J. M. Cowdery, J. S. Tulenko, D. Schoenfeld, S. Henderson, R. Stewart, M. Inskeep, "Reliable Wireless Data Acquisition and Control within Nuclear Hot Cell Facilities," Proceedings of ICONE 8, the 8th International Conference on Nuclear Engineering, Baltimore, MD, April 2-6, 2000
5. Cowdery, J and J. Kurtz, "Modular Wireless Data Acquisition System for use in High Radiation Environments," technical report on NEER Project DE-FG-07-98ID13636, submitted to National Labs-West, September 2000.
6. University of Florida Electronic Communications Laboratory and Nuclear and Radiological Engineering Department Technical Report, "Radiation Tolerance Testing in Support of Wireless Communication System Development," technical report on NEER Project DE-FG-07-98ID13636 submitted to Argonne National Labs-West, July 2000.

Presentations:

1. Kurtz, J. L., Cowdery, J. M., J. S. Tulenko, Presentation to Argonne National Laboratory-West, on DOE NEER Project DE-FG07-98ID13636, "Reliable Wireless Communciations for Nuclear Hot Cells," August 3, 1998.
2. Kurtz, J. L., J. M. Cowdery, J. S. Tulenko, D. Schoenfeld, S. Henderson, R. Stewart, M. Inskeep, "Reliable Wireless Data Acquisition and Control within Nuclear Hot Cell Facilities," Presented at ICONE 8, the 8th International Conference on Nuclear Engineering, Baltimore, MD, April 2-6, 2000
3. Cowdery, J. M., J. L. Kurtz, J. S. Tulenko, Presentation to Argonne National Laboratory-West, on DOE NEER Project DE-FG07-98ID13636, "Reliable Wireless Data Acquisition and Control within Nuclear Hot Cell Facilities," August 21, 2000.